Impact of Typhoons on the Western Pacific Ocean DRI: Numerical Modeling of Ocean Mixed Layer Turbulence and Entrainment at High Winds

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LONG-TERM GOALS

This study contributes to our long-term efforts toward understanding:

- Mixed layer dynamics
- Processes that communicate atmospheric forcing to the ocean interior

OBJECTIVES

This collaborative effort aims to measure and model the response of the upper ocean to strong typhoons both in simple, open ocean conditions and in the more complex conditions caused by ocean eddies, the Kuroshio and complex, shallow bathymetry. The measurements and modeling includes the impact of surface waves, air-sea fluxes and the temperature, salinity and velocity structure of the upper ocean. The goals of this effort are to understand key upper ocean processes, test upper ocean models, test key parameterizations of upper ocean physics used and study the feedback from the ocean to typhoon intensity.

APPROACH

The approach of the the Large Eddy Simulation (LES) modeling component is to use field observations to forcel LES numerical cases and use model-data comparison to the theoretical basis of mixed layer parameterizations. The strategy is to test our physical theories and parameterizations of mixed layer dynamics against data by incorporating them realistically in turbulence-resolving LES models with embedded virtual measurements. Verification of the underlying theories can then be achieved through direct model-data comparison, using observations of ocean waves and turbulence under a wide range of oceanic conditions, and leading to improved parameterizations of upper ocean turbulence. The strong and isolated wind forcing in tropical cyclones provides an ideal environment for testing theories and parameterizations of the role of surface waves in the ocean mixed layer. This follows similar work in CBLAST exploiting the comprehensive view of boundary layer turbulence made possible by the combination of Lagrangian float and EM-APEX measurements.

WORK COMPLETED

A series of Typhoon LES model cases has been carried out to simulate the upper ocean response to spectrally distributed surface waves with wind-wave coherence varying with frequency. These are

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14. ABSTRACT
This collaborative effort aims to measure and model the response of the upper ocean to strong typhoons both in simple, open ocean conditions and in the more complex conditions caused by ocean eddies, the Kuroshio and complex, shallow bathymetry. The measurements and modeling includes the impact of surface waves, air-sea fluxes and the temperature, salinity and velocity structure of the upper ocean. The goals of this effort are to understand key upper ocean processes, test upper ocean models, test key parameterizations of upper ocean physics used and study the feedback from the ocean to typhoon intensity.

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based on the spectra modeled and measured during CBLAST hurricanes. These simulations are being used to parameterize the effect of surface wave spectra on mixed layer energy and entrainment during hurricanes.

RESULTS

The LES models forced by wind stress and model surface waves via the Craik-Leibovich vortex force can predict mixed layer vertical kinetic energy and entrainment rates, provided that the surface wave field and drag coefficient are properly specified. A simulated case at Lagrangian float G22 below the wind maximum of Hurricane Frances (2004) is shown in Fig. 1.

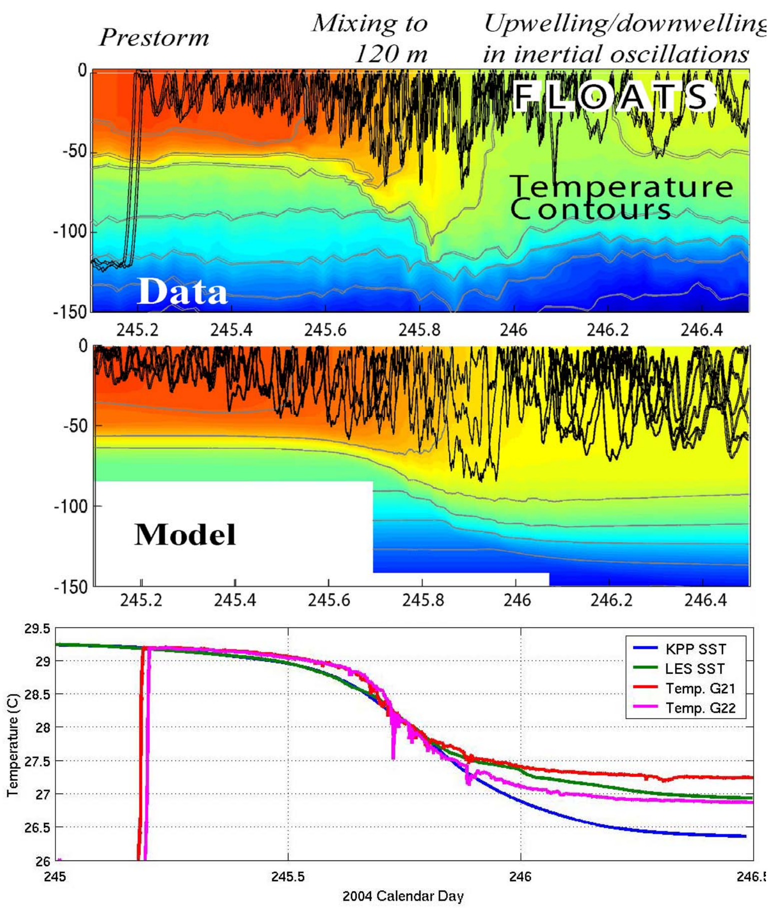

Figure 1: (top) shows Temperature (co and contours) from EM and Lagrangi floats G21 and G22 (Sanford, D'Asaro overlaid with Hurricane Frances Lagrangian float observations. (middle corresponding LES model with floats (middle), vs. time and depth (m). Mode float depth distributions and vertical T agree well with the data. Proper predic of mixed layer depth changes will requ further specification of upwelling due larger scale dynamics, but LES sea surface temperature (bottom) compare well with Lagrangian float G22. An L equivalent column model based on KP matches LES evolution as the wind ris but predicts significantly more entrainment and cooling as wind drops and compares less favorably with observations.

The evolution of mixed layer depth agrees until larger scale upwelling (D'Asaro et al 2007) intervenes. Even beyond that, the evolution of surface temperature continues to agree relatively well. Other its role in the surface stress, no additional contributions from wave breaking appear to be necessary for prediction of mixed layer VKE or entrainment deepening. Comparisons with a column model based on the K-Profile Parameterization (KPP) agree when the wind is rising, but not in the rear of the storms when seas are confused and KPP entrainment is driven more by inertial shear in the pycnocline.

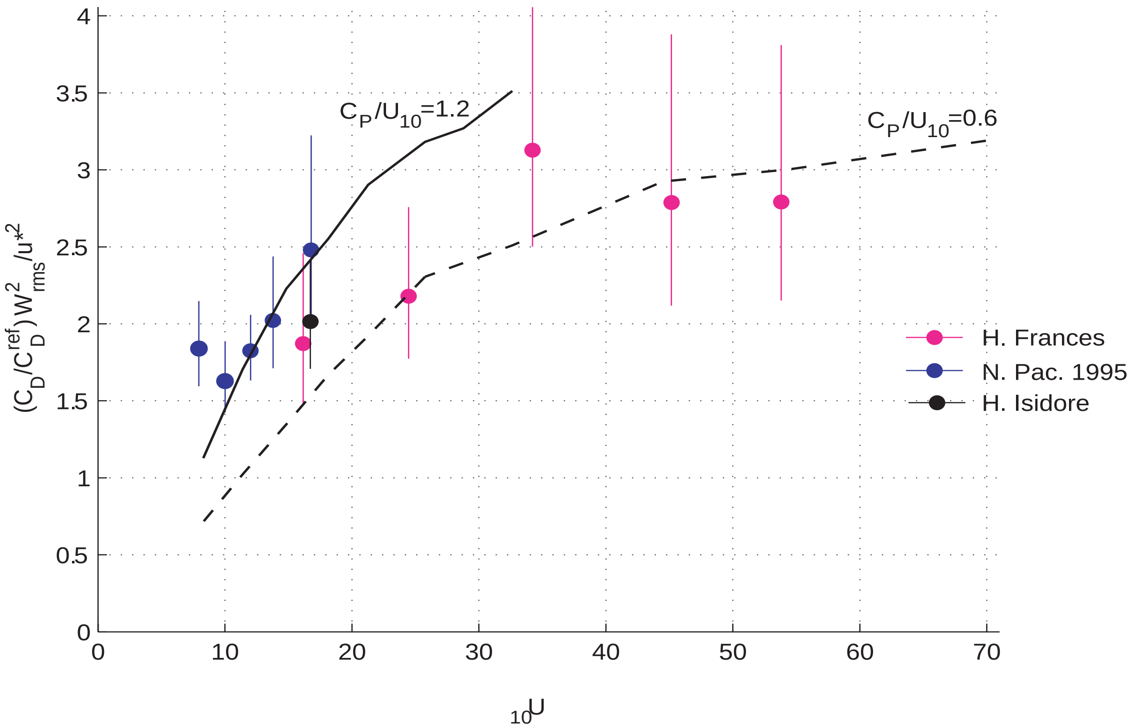

Figure 2: Float observations (color) and LES predictions (black) of bulk mixed layer vertical TKE scaled on wind kinetic energy U_{10}^2 (using C_D^{ref}=1e-3). Under moderate winds (blue symbols) simulations assuming mature (C_p/U_{10} =1.2, solid) seas fit well. Under extreme winds (CBLAST – purple & black), simulations assuming young (C_p/U_{10} =0.6, dashed) seas and a saturating drag coefficient fit well. Turbulence in the ocean mixed layer cannot therefore be specified from wind speed alone; wave properties and a proper drag coefficient are also needed. Data with a wide range of variability in wind speed and wave age is needed to test parameterizations of these effects. Typhoons are an ideal environment for this. Proper modeling of Typhoon boundary layers requires an understanding of these effects.

An LES-derived parameterization (Harcourt and D'Asaro, 2008) based on wind speed and wave age, assuming pure wind seas, can predict measured mixed layer vertical kinetic energy (D'Asaro, 2001) under a wide range of conditions. The magnitude of VKE figures prominently in several mixed layer models, including KPP. The VKE is scaled by wind stress is a function of a modified turbulent Langmuir number $La_{SL} = (u^*/(u_{SL}^S - u_{ref}^S))^{1/2}$, based on the friction velocity u^* and the near-surface average u_{SL}^S of the Stokes drift u^S. A reference level u_{ref}^S from within the lower mixed layer is subtracted because vortex force production must vanish for a mixed layer with uniform Stokes drift. A distinction of this parameterization is that it applies equally to Langmuir turbulence in realistic wind seas with distributed spectra as well as to more the more widely considered idealized cases with monochromatic surface waves. Fig. 2 shows comparisons for both the very young seas found at high winds in Typhoons and Hurricanes, and for fully developed mature seas found at more moderate wind speeds in mid-latitude winter storms, demonstrating the range of conditions predicted withing the framework of Craik-Leibovich theory by this parameterization.

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Current upper ocean boundary layer models typically parameterize the effect of wind and waves using the friction velocity u_*. For example, one measure of the rate of entrainment of fluid into the mixed layer is the vertical buoyancy flux $\overline{w'b'}$ integrated over the mixed layer, This equals the rate at which mixing converts VKE into potential energy and can be quantified by an entrainment velocity scale $w_e^3 = \int_{-H_{ml}}^{0} \overline{w'b'}dz$. For a well-mixed layer of depth H_{ML} with a sharp buoyancy step Δb at its base, $w_e^3 = \frac{1}{2}\Delta b H_{ML} \frac{d}{dt} H_{ML}$. In the case of no surface buoyancy forcing and no subsurface shear, a simple parameterization is $w_e^3 = c_0 u_*^3$, giving the rate of mixed layer deepening in terms of the wind forcing. LES model results show the entrainment efficiency w_e^3 / u_*^3 from steady-state LES cases for wind-wave forcing with varying H_{ML} and wave properties. The entrainment velocity increases with decreasing Surface Layer Langmuir number La_{SL} (i.e. with stronger wave forcing) with a functional form $w_e^3 = c_1 u_*^3 + c_2 u_*^3 La_{SL}^{-2}$. The first term is the wind input with no waves; the second represents the additional wind-wave input due to the C-L force. An empirical choice of fixed c_0 would implicitly assume a fixed value of La_{SL}. The main focus of current research efforts in the Typhoons DRI is to extend this parameterize these effects of waves on mixed layer turbulence to understand how the interaction between wing and waves impacts vertical mixing rates at the surface below Typhoons.

IMPACT/APPLICATIONS

Surface waves are believed to play a key role in the upper ocean boundary layer, yet do not appear explicitly in any of the major boundary layer parameterizations used in ocean circulation or climate models. Addressing this defect will lead to mixed layer models with turbulence intensity and entrainment efficiency, scaled by wind stress, that increase with surface wave age, in the presence of swell. While subsurface shear may dominate pycnocline mixing under inertially resonant wind forcing conditions, variability in mixed layer energy due to surface waves will play a significant role in deepening the layer when this is not the case. A boundary layer model that includes sea state dependencies, in addition to the usual dependencies on surface stress, buoyancy flux, and subsurface shear, will ultimately be more accurate than one which does not.

RELATED PROJECTS

None

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